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in generation of the response, this manipulation would also especially benefit small arrays, and should have a similar effect on the array-size function. In sharp contrast to these expectations, we found no effect of our manipulations on the time to retrieve information from visual memory. The results add support to an explanation of the effects of storage time which attributes them to the rapid transformation of an initial random-access visual memory into a sequential-access memory. *Comments:*

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Direct Access by Spatial Position in Visual Memory: 3. The roles of uncertainty about position, target, and response in information retrieval

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1. Introduction: Mechanisms underlying the dramatic effect of storage time on retrieval of visual information

In previous studies we have found that the effect of array size (2-6 digits) on the latency to name a target element specified by its spatial location in a brief display increases rapidly with probe delay. (See Sternberg, Knoll, & Turock, 1985, 1986.) For early spatial-location probes the effect of array size is negligible, suggesting that the initial internal representation of the array has the property of *direct access* (or "random access"). Retrieval-time measurements change dramatically with probe delay, however: After delays of only a few hundred milliseconds, the effect of array size has become substantial (and is remarkably linear). One interpretation is that the property of direct access is rapidly lost, and that the internal representation has been transformed from a *random-access memory* into a *sequential-access memory* — one in which retrieval is

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accomplished by means of a sequential search.

Instead of reflecting only a transformation of the internal representation that alters the operation by which its elements are accessed, the change in the array-size effect may also reflect changes in the durations of other sets of operations that take place between presentation of the probe and emission of the response. Indeed, although we regard it as unlikely, it is conceivable that rather than being rapidly lost, the property of direct access is preserved for a second or more, and that the *entire* change in the array-size effect with probe delay results from changes in the durations of other sets of operations. One such set of operations is associated with the processing of the probe, which presumably *precedes* access to the internal representation of the array, and includes the detection and encoding of the probe and the discrimination of the location it designates. Another such set of operations is associated with generation of the response, which presumably *follows* access to the internal representation of the array, and includes discrimination of the representation of the marked element once it has been accessed, determination of its name, and organization and execution of the naming response.

It seems highly likely that the durations of both of these sets of operations are influenced by storage time, especially as the linear array-size function $RT(s)$ that relates mean reaction time RT to array size s has a (zero) intercept (which probably reflects their durations) that becomes substantially smaller as the delay increases. The issue is whether the *slope* of the $RT(s)$ function (which we use as a measure of the array-size effect) also reflects changes in those durations — that is, whether array size and delay interact in influencing those durations.¹

The purpose of the experiment described in the present report is to begin to assess what contributions, if any, are made to the influence of delay on the array-size effect from changes with delay in the times required to process the probe and generate the response. With respect to processing of the probe, one factor that provides a potential source of such an effect is the change with delay in the subject's knowledge of the set of alternative locations where the probe may appear (*spatial uncertainty*). With respect to generating the response, a factor that provides a potential source of such an effect is the change with delay in the subject's knowledge of the set of alternatives from which the target element

1. One possible argument that bears on such dependence derives from the linearity of the $RT(s)$ function. Plausible processes of accessing the internal representation of an array element (such as sequential search) can of course be found that generate linear effects of array size. In contrast, the time to execute stimulus-response associations, as in numeral naming, is generally believed to increase linearly with $\log n$ or $\log (n-1)$, where n is the number of alternatives. (Welford, 1980). On the other hand, little is known about the form of the dependence of the time to discriminate location on the number of potential locations, so that linearity is not excluded.

(which has to be named) will be drawn (*target and response uncertainty*). Our experiment incorporated attempts to manipulate these two varieties of uncertainty directly.



Figure 1

2. An outline of the method and results of earlier studies

In this section we describe the essentials of the method and results of earlier studies with spatial-location probes in which both array size and probe delay were manipulated, so that readers will not have to be thoroughly familiar with previous reports.

We addressed locations in memory with a spatial-location probe that consisted of a *visual* marker that designated a *single* target element.² A sample display from one series of experiments is shown in Figure 1. It contains three constituents, which could appear and disappear at different times: One is the array of digits, here of size four; Another is a pair of dots, one above and one below the location of each digit ("registration dots"); The third is the probe, two vertical line segments, one above and one below the location of the target digit. The subject's task was to name the target digit as rapidly as possible; we measured vocal *RT*. Subjects were paid for speed and penalized for errors. We varied array size from trial to trial, and probe delay from block to block.³

2. In one experiment we found that tactile and visual markers produced similar results (Sternberg, Knoll, & Turock, 1986).

3. For example, in our first series of experiments array size was $s = 3, 4, 5$, or 6 , and probe delay (in msec) was $-50, 0, 150, 350, 650, 950, 1650$, or 3450 .

Three of the possible time sequences of array, registration dots, and probe are described in Figure 2. In all three examples, the correct response is to pronounce the word "eight." In the first example, probe delay is zero. The 50 msec probe and the 150 msec array turn on simultaneously. In the second example the probe immediately follows the array, so the probe delay is 150 msec. The final example shows a long delay. Here the dots are especially useful in reducing difficulties of registration of array and probe. The dots stayed on until the response was detected.

	Simultaneous Probe	Probe Immediately After	Delayed Probe
Time ↓	$\begin{array}{c} \\ \dot{3} \ 8 \ \dot{9} \\ \end{array} \left(\begin{array}{c} 50 \\ \text{msec} \end{array} \right)$		
	$\begin{array}{c} \dot{3} \ \dot{8} \ \dot{9} \\ \left(\begin{array}{c} 100 \\ \text{msec} \end{array} \right) \end{array}$	$\begin{array}{c} \dot{3} \ \dot{8} \ \dot{9} \\ \left(\begin{array}{c} 150 \\ \text{msec} \end{array} \right) \end{array}$	$\begin{array}{c} \dot{3} \ \dot{8} \ \dot{9} \\ \left(\begin{array}{c} 150 \\ \text{msec} \end{array} \right) \end{array}$
	$\begin{array}{c} \cdot \cdot \cdot \\ \cdot \cdot \cdot \end{array}$	$\begin{array}{c} \cdot \ \cdot \\ \cdot \ \cdot \\ \left(\begin{array}{c} 50 \\ \text{msec} \end{array} \right) \end{array}$	$\begin{array}{c} \cdot \cdot \cdot \\ \cdot \cdot \cdot \\ \left(\begin{array}{c} 650 \\ \text{msec} \end{array} \right) \end{array}$
		$\begin{array}{c} \cdot \cdot \cdot \\ \cdot \cdot \cdot \end{array}$	$\begin{array}{c} \cdot \ \cdot \\ \cdot \ \cdot \\ \left(\begin{array}{c} 50 \\ \text{msec} \end{array} \right) \end{array}$
			$\begin{array}{c} \cdot \cdot \cdot \\ \cdot \cdot \cdot \end{array}$

Figure 2

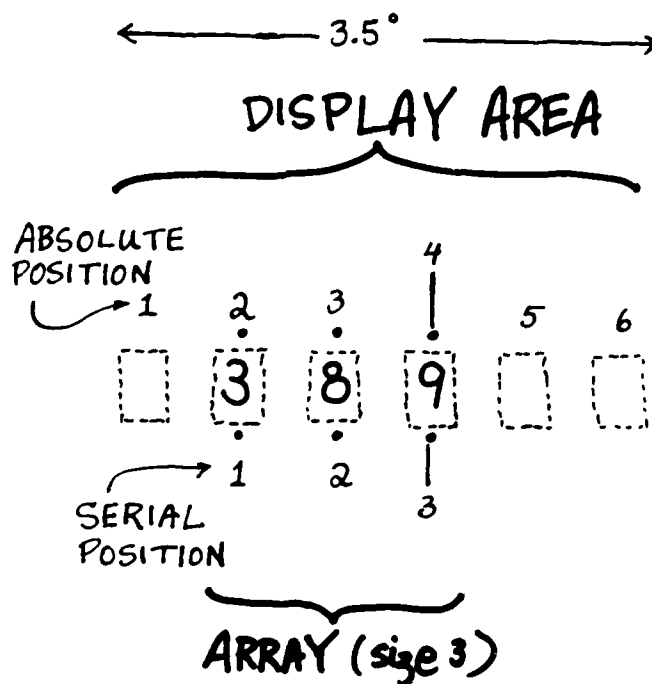


Figure 3

Among the differences between our experiments and those of Averbach and Coriell (1961), three seem especially important. First, rather than overloading the memory we used small arrays, so that subjects were almost always correct; the average error rate was about 3%. Second, we applied time pressure, and the primary measure was *RT*. Finally, we varied the number of elements in the array, since our main interest is in the effect of array size on mean *RT*.

Some of the details of design and procedure are best considered in the context of Figure 3. The display area contained six potential element locations (*absolute positions*). At the start of a trial, subjects fixated in the center of this area. To avoid confounding number of elements (*array size*) with their separation, we placed elements in *contiguous* locations. To reduce the confounding of array size with retinal eccentricity, we placed the arrays at all possible positions within the display area, in our standard procedure.⁴

There are of course several factors other than array size that may influence *RT* in the spatial-probe procedure: for example, position of array within the display area (*array position*), position of probe (and target element) within the display area (*absolute position*), and position of the target element within the array (*serial position*). It is not possible to arrange for all these factors, together with

4. The leftmost element in an array of size $s = 4$, for example, could occupy absolute positions 1, 2, or 3.

array size, to be mutually orthogonal. Equally-weighted averaging over array positions is biased, in the sense of producing different distributions of absolute positions for different array sizes.⁵ A more sophisticated multiple regression analysis, in which the position effects are estimated and removed, suggests, however, that the simple analysis is not far off. (Evidence favoring the regression method, but also showing that the bias associated with simple averaging is not great, is presented in Appendix 1.) For a relatively complete description of our analysis method, see Sternberg, Turock, & Knoll, 1986. In that report we describe the regression model and discuss our preference for a type of robust regression as a fitting procedure. The same sort of analysis is one of those performed in the study described in the present report.⁶

Results show that the effect of array size on the latency to name a visually marked element in a brief display increases rapidly with probe delay, revealing a change in representation. For early probes the effect is negligible, indicating direct access; for late probes the effect is a linear increase, indicating a failure of selective attention and suggesting search.

5. Suppose that an array of size s , each of the $7-s$ possible array positions occurs equally often, as does each of the s possible serial positions of the target element. An equally-weighted mean over the $(7-s)s$ resulting combinations then produces a distribution of absolute positions that varies with array size. (The frequencies of probes over the six possible absolute positions are in proportion to (1:2:3:3:2:1) for $s = 3$ and 4, to (1:2:2:2:2:1) for $s = 5$, and to (1:1:1:1:1:1) for $s = 6$. The resulting mean distance from fixation point to probe (mean eccentricity), measured in absolute-position units, is 1.17, 1.17, 1.30, and 1.50 for $s = 3, 4, 5$, and 6, respectively. Because RT tends to be longer with greater eccentricity, smaller arrays are favored. Unless these effects are removed, mean RT might then artifactually appear to increase with array size.

The smaller arrays may also be favored by the distribution of serial positions, because end positions tend to produce shorter RT s, and the proportion of positions that are end positions ($2/s$) decreases with s . Whether this end effect should be removed, however, in estimating a "pure" effect of array size, may depend on how it is interpreted: If it is an effect of lateral masking on acuity, e.g., it should be removed, whereas if it is an effect of the order of a self-terminating search, e.g., it should not.

6. In the multiple linear regression analysis we separately fitted an additive model to the data for each probe delay and each subject. We incorporated effects of array size, target element, and serial position within array size, as well as two separate effects of absolute position, one for end elements (serial positions 1, s), and the other for interior elements (serial positions 2, 3, ..., $s-1$).

3. Possible effects of delay on processing of the probe: Spatial uncertainty reduction

As Figure 3 indicates, the probe (and the probed element) can appear in any one of six display locations. From the subject's viewpoint, when the probe is early all six locations are possible. Once the array is presented, however, information is available about where the array is positioned in the display space — i.e., which are the filled locations. It seems likely that as the delay increases the subject can acquire this information; this makes it possible that in processing the probe she makes use of the information about which of the locations are filled. For a 6-element array, there is no reduction in spatial uncertainty relative to an early probe, but for smaller arrays, the acquired information would serve to reduce spatial uncertainty. That is, for a delayed probe, the subject may learn from seeing the array what the set of possible target and probe locations might be. (Because arrays in our experiments contain at least two elements, such knowledge can reduce, but not eliminate, spatial uncertainty.) If attention in visual space is allocated correspondingly, and if discrimination of the probe's location and/or the target's identity is better when attention is less widely dispersed (or when attention is at the probe's location with higher probability) then the discrimination of the location of a delayed probe and/or identification of the target will be faster with smaller arrays. *RT* would then increase with array size when the probe is delayed, because of an increase with array size in the time to discriminate the probe's location, and/or in the time to identify the target.

Partly because spatial uncertainty might influence either or both of these processes, it is not clear how previous studies should guide our expectations about the present one. Another difficulty is that most studies compare uncertain to certain conditions, rather than comparing different levels of uncertainty. Furthermore, many of the studies that otherwise appear relevant have used accuracy rather than latency measures, and are thus based on subjects working under conditions of low accuracy.

Nonetheless we mention a few of the findings that may be relevant. Location discrimination accuracy suffers from an increase in number of alternative locations (e.g., Hake & Garner, 1951; Shaw, 1984). But whereas Shaw has shown that localizing a flash among a small set of locations (possibly akin to localizing our probe) is impaired by an increase in number of locations, the impairment is small enough such that it can be fully explained by effects at the decision level, and does not require us to assume a loss of information due to increased division of attention. We do not know what this finding implies about latency data, however. On the other hand, Shaw also showed that the corresponding impairment in the accuracy of localizing a target letter (rather than a light flash) with an increase in spatial uncertainty does require assuming such a loss of information.

Several studies of form detection and discrimination show effects of spatial uncertainty. Thus, the accuracy of identifying a target letter presented in an otherwise blank field (van der Heijden, Schreuder, & Wolters, 1985) or discriminating in which

of two time intervals a grating appears (Davis, Kramer, & Graham, 1983) is increased by eliminating uncertainty about its locus. Among studies in which *RT* rather than accuracy was the principal measure, findings are complex: Eriksen & Hoffman (1973, 1974) showed that the time to name a single letter in an otherwise blank field is reduced by advance information about its position. On the other hand, Eriksen & Schultz (1977) showed that when spatial uncertainty was reduced, but not eliminated, the naming latency under the same conditions did not change reliably.

When the target to be discriminated is embedded among other elements in the field, rather than appearing alone, then discrimination time is reduced by advance information that provides the probability distribution of target positions (Shaw, 1978), or the particular position (Holmgren, 1974).

These findings suggest that spatial uncertainty might have an effect in our experiments. On the other hand, in LaBerge's (1983) demonstration that attention can be focussed to different degrees within an array of characters (as shown by the target-discrimination *RT*) he also found that focusing of attention is costly: even in the location producing the fastest response under focussed conditions, *RT* is longer than in the corresponding location when attention is more dispersed. It is therefore possible that whereas the use of advance spatial information to differentially allocate attention may be helpful under conditions where distractor noise is the controlling factor and accuracy is low, it may be costly under conditions of high-accuracy and speeded response.

4. Method: Direct manipulation of spatial uncertainty

According to the hypothesis described in the section above, the subject makes use of information in the array to reduce spatial uncertainty about the probe during the time between presentation of array and probe. We know that with a probe delay of 650 msec most of the change in the pattern of retrieval times with delay has taken place. Insofar as variation in spatial uncertainty plays a role in generating this pattern, we should therefore find an effect of the size of the set of possible probe locations if information about this set is presented 650 msec before the probe. This is what we did, preceding the probe by a dot above and below each of the locations that would be occupied in the forthcoming array.⁷ The array-probe delay that we used under this condition of advance location information (-50 msec, which we describe as an "early probe") was one that normally produces a negligible effect of array size on latency.

7. In our standard procedure, described in Figures 1, 2, and 3, "registration dots" are presented simultaneously with the elements of the array rather than in advance, and remain visible after array offset until the response occurs.

Insofar as the reduction in spatial uncertainty for small arrays reduces the time required for probe-location discrimination, the advance information should cause mean *RT* to increase with array size, even with an early probe.

Two assumptions that are critical to our method of testing for effects of spatial uncertainty should be brought out. First, in the standard condition the source of any information about possible probe locations is the array itself, which consists of a row of digits, each with a pair of registration dots. The experimental condition described above uses just a set of registration-dot pairs, without digits. Inferences based on this condition depend on the assumption that the dot pairs alone, without the array elements, will effectively convey information about possible probe locations.

Second, although we are interested in the effect of advance information about possible probe locations on performance with a delayed (e.g., 650 msec) probe, the experimental condition involves measurement of its effect on performance with an early (-50 msec) probe. We chose this design because an extreme form of the hypothesis under test asserts that were it not for an effect of array size on spatial uncertainty, performance at probe delays of -50 msec and 650 msec would not differ with respect to the magnitude of the array-size effect: Both conditions would reflect the direct-access property. Inferences based on the experimental condition depend on the assumption that the net effect of spatial uncertainty on the duration of processes triggered by the *early* probe will be the same as (or no smaller than, or no greater than, depending on the inference of interest) its net effect on the duration of processes triggered by the *delayed* probe.

As discussed below, in half of the conditions of the present experiment the arrays are always centered about the fixation point, rather than being presented, as in our standard conditions, in all possible subsets of (contiguous) locations among the six possible element locations. Given an array that is known to be centered, the additional information conveyed by the advance location information in the present condition indicates only how wide the array is.

5. Possible effects of delay on generating the response: Reduction of uncertainty about target and response

Before presentation of an *early* probe the subject has no information that limits the target stimulus or the response to a set of alternatives smaller than the full set of ten digits. That is, from the subject's viewpoint the response to be generated and the representation of the target stimulus to be decoded can be any one of the ten digits with equal likelihood. As the subject processes the array while awaiting a *delayed* probe, however, she assimilates information about which digits it contains. As this information is assimilated, stimulus and response uncertainty are reduced; the smaller the array, the greater the reduction. Furthermore, the less the stimulus and response uncertainty, the less time might be taken by decoding the representation of the target element and organizing and executing the response. *RT* would therefore increase with

array size, not because of an increased time to gain access to the internal representation of the target element, but because of the time taken by decoding this representation and generating the response.

How large an effect of uncertainty about target stimulus and response might we expect? The most pertinent data come from estimates of the effect of the number, n , of stimulus-response pairs on mean RT , when the stimuli are isolated numerals and the responses are their spoken names. Such estimates vary from study to study, and depend, for example, on legibility of the numerals; for the range $2 \leq n \leq 6$ they tend (in this case of unusually high "stimulus-response compatibility") not to exceed about 20 msec (Sternberg, 1969; Teichner & Krebs, 1974; Theios, 1975). That this uncertainty effect is substantially smaller than the array-size effect we observe over the corresponding n -range at a probe delay of 650 msec (whose magnitude is approximately 200 msec) suggests that the influence of array size on stimulus and response uncertainty can explain no more than a small fraction of the effect of array size. The relevance of the numeral-naming data can be questioned, however, for at least two reasons: First, the numeral to be named in the experiments at issue is displayed in the context of one or more others rather than in isolation, and second, the basis for naming is not (the internal representation of) a currently displayed numeral, but some (unknown) memory representation of that numeral.

6. Method: Direct manipulation of target and response uncertainty

To assess the effect of uncertainty about target stimulus and response we devised a condition in which we required the subject to name in advance of the array the same set of numerals that would be contained within it. Thus, on each trial, the numerals that were to be presented in the array were first displayed sequentially, in one locus, and in a sequence that was random with respect to their spatial locations in the array. The subject was required to name them as they appeared. Shortly thereafter the probe appeared, followed 50 msec later by the array. (The probe delay was thus -50 msec.) When the probe was displayed, the subject had thus recently produced the set of possible responses, and had recently encoded the set of numerals. Insofar as the resulting reduction in stimulus and response uncertainty (greater for smaller arrays) reduces the time required for decoding and response-generation operations, the advance information should cause mean RT to increase with array size.

As we mention above and discuss below, in half of the conditions of the present experiment arrays are always centered about the fixation point. For a centered array, the number of elements it contains fully specifies the set of locations it occupies. It follows that with centered arrays the advance target and response information in the present condition also has the potential for reducing *spatial* uncertainty to the same extent as advance presentation of the relevant subset of registration dots.

Priming of encoding. Because our procedure for manipulating target and response uncertainty involves the encoding of array numerals shortly before the array appears, it permits another factor to produce an effect of array size. There is evidence that use of a pattern-identification mechanism activates that mechanism in such a way that until the activation declines, the mechanism operates more efficiently (Walker, 1978; Proctor, 1981; Kroll & Shepeler, 1985). Suppose that after the onset of the array in the standard procedure, the subject encodes array elements into memory, and that the encoding process is thus primed so that if the same element must again be encoded within a short period of time (to generate the target response) its encoding proceeds more rapidly. Suppose further that the fewer the elements in the array, the more the average amount of priming per element at the time the probe is presented. Then with larger arrays encoding of the target element would proceed more slowly. Thus latency could increase with array size, not because of the increased time to find the representation of the element in the location designated by the probe, but because once that representation was found, its encoding would proceed more slowly. If subjects are required to encode the array numerals before the display of an early probe and an array, as in the present procedure, then delay of the probe should not be necessary for any such array-size effect to be evident.⁸

7. Details of procedure

In the present study we examined four conditions in which information and/or delay was manipulated; we refer to these as information/delay conditions. Two are the experimental conditions, *advance location information* (described in Section 4 above) and *advance identity information* (described in Section 6 above). The other two are control conditions that closely approximate our standard procedure: *early-probe control* and *late-probe control*. (We abbreviate these designations as *Loc*, *Ident*, *Early* and *Late*, respectively.) Sequences of events in three of the conditions are described in Figure 4.

8. This alternative possibility complicates the interpretation of a positive result (i.e., a larger effect of array size in this experimental condition than in the corresponding control condition), while at the same time permitting more powerful implications to be drawn from a negative result.

Time (msec)	Advance Location Information	Early Probe Control	Late Probe Control
-650
-50
0	3̣ 8̣ 9̣	3̣ 8̣ 9̣	3̣ 8̣ 9̣
+50
+650	(Response)	(Response)

Figure 4

In the condition of advance location information, the critical feature was a set of registration dots appropriate for the forthcoming array and preceding array onset by 700 msec, which remained visible until the response was detected. To provide a warning, a fixation dot was displayed 1300 msec before the onset of the registration dots, and this, in turn, was preceded by a warning noise in the subject's headphones. The probe preceded the array by 50 msec.⁹ In devising this condition we had in mind the standard procedure with a probe delay of 650 msec, in which information about the set of possible probe positions is available 650 msec before the probe appears.

Early presentation of the registration dots in the condition of advance location information has the potential of reducing temporal as well as spatial uncertainty, by providing an additional visual warning. For both the early-probe (-50 msec delay) and late-probe (650 msec delay) control conditions we therefore preceded the array by 700

9. Note that the consequence of this asynchrony between probe and array is that the interval between the onsets of spatial information and probe is 600 msec, rather than 650 msec, although the delay between the onset of spatial information and the availability of *both* probe and array information is 650 msec. The issue of which delay is the appropriate one to match in experimental and standard conditions will prove to be unimportant, given our results.

msec with the full set of six pairs of registration dots, to provide a comparable warning but without influencing spatial uncertainty. The initial events on trials in our control conditions thus consisted of a warning noise, then a single fixation dot, and 1300 msec later, the set of six pairs of registration dots. Otherwise the control conditions incorporated the same sequences of displays as in our standard procedure.

In the condition of advance identity information, the displays were the same as in the early-probe control condition except that after the warning noise and before onset of the fixation dot the digit elements in the forthcoming array were displayed sequentially, in random order, at the center of the display area. They were presented at a rate of two and one-half digits per second, each digit having a duration of 250 msec, and subjects named them as they appeared.

Under all conditions, subjects were exhorted to point their eyes at the fixation point when it appeared and to maintain fixation throughout the trial; they reported doing so when queried.

8. Issues of experimental design

In Section 6 of Sternberg, Knoll, & Turock (1986) we discuss some of the issues in designing an experiment to assess an array-size effect at several probe delays. One difficulty is that other (secondary) experimental factors that might have effects on *RT*, or are known to have such effects, may also vary from trial to trial. Examples of such secondary factors are the target element's *identity*, its *serial position* within the array, and its *absolute position* within the display area.

Ideally we would arrange that all secondary factors are independent of array size and probe delay, either by being held constant while these primary factors are varied, or by being varied orthogonally with the primary factors. With respect to array size there are inherent difficulties in satisfying such requirements; therefore any design reflects a set of compromises. For various reasons the desired orthogonality cannot be achieved. For example, regardless of the size of the experiment, levels of absolute position in the display area and of serial position in an array of given size cannot both be made orthogonal with array size. And unless an experiment is impractically large, target identity cannot be made orthogonal with all other factors. It follows that one cannot extract a "pure" measure of the array-size effect simply by employing the usual practice with balanced designs: assuming no interaction of this effect with levels of secondary factors, and averaging over them (a *cell-means analysis*). Instead we have chosen to design experiments so as to permit the desired "pure" measure to be extracted from a multiple linear-regression analysis.

These issues, as well as some considerations that apply especially to the present experiment, should be illuminated by reference to the design alternatives illustrated in Figure 5.

Centered Array		Orthogonal array & Serial Position	
Absolute Position		Absolute Position	
1	2 3 4 5 6	1	2 3 4 5 6
$s = 2$	X-X	X-X	
		X-X	
		X-X	
		X-X	
		X-X	
$s = 3$	X-X-X	X-X-X	
		X-X-X	
		X-X-X	
		X-X-X	
		X-X-X	
$s = 4$	X-X-X-X	X-X-X-X	
		X-X-X-X	
		X-X-X-X	
		X-X-X-X	
		X-X-X-X	
$s = 5$	X-X-X-X-X	X-X-X-X-X	
		X-X-X-X-X	
		X-X-X-X-X	
		X-X-X-X-X	
		X-X-X-X-X	
$s = 6$	X-X-X-X-X-X	X-X-X-X-X-X	
		X-X-X-X-X-X	
		X-X-X-X-X-X	
		X-X-X-X-X-X	
		X-X-X-X-X-X	

Figure 5

The diagram on the right illustrates a design in which arrays of each size from size $s = 2$ through size $s = 6$ are presented at each possible array position within a six-position display area, and for each array position, each serial position is tested equally often. The rows of numbers reflect the relative frequency with which each absolute position is tested for each array size. Except for array size $s = 6$, such balancing over serial position and array position is associated with an unbalanced set of absolute positions. For $s = 2$ and $s = 5$, elements in parentheses indicate adjustments that take the form of added trials whose effect is to balance absolute positions and equalize the number of trials per array size, but which also serve to

unbalance array position and absolute position for those array sizes. (Circles indicate array elements that are presented but not tested.) With or without these adjustments, it is clear that simply averaging over serial position and array position will not provide an estimate of the pure array-size effect that we seek to assess. However, because arrays are *distributed* over the display area, rather than being *centered*, so that all absolute and serial positions are tested with each array size, it is possible to extract such an array-size effect by means of multiple regression.

An alternative design, involving just centered arrays, is illustrated in the diagram on the left. Arrays of odd size are omitted, to restrict elements to the same six absolute positions. With this design the disentangling of array-size and absolute-position effects even by means of regression requires unpalatably strong assumptions about serial-position effects (one possibility is to assume flat serial-position functions¹⁰); straightforward averaging is afflicted by serious confounding of array size and eccentricity. Because more eccentric targets and probes produce longer *RTs*, such confounding would inflate and probably distort any array-size effect.

Despite these difficulties associated with a design using centered arrays, we chose to use sessions restricted to just such arrays (of sizes $s = 2, 4$, and 6) in the present experiment, along with other sessions in which subjects worked with distributed arrays (of sizes $s = 2, 3, 5$, and 6). Our main reason for including sessions with centered arrays is associated with the condition of advance location information which, with distributed arrays, might strongly tempt the subject to move her eyes to the center of the area to be occupied by the forthcoming array to reduce the mean retinal eccentricity of array elements and probe locations, despite our exhortations to subjects to maintain fixation in the center of the display area.¹¹ Given centered arrays, the location information indicates the width of the forthcoming array rather than its location, and might, for example, influence the extent to which attention is distributed over the display area, but would seem less likely to induce an eye movement. The difficulty associated with centered arrays — the severe confounding of array size with retinal eccentricity, and the resulting bias in our estimate of the array-size effect — may be less serious in the present study than others, because the direction and magnitude of the bias in the conditions that enter into critical comparisons (experimental conditions versus the early-probe control condition) may be the same. Furthermore, by combining data from the sessions with centered and distributed arrays in a single regression analysis, to be described below, we were able to "correct" the

10. A *serial-position function*, $RT_s(p)$ can be defined for each array size, s and relates mean *RT* to the left-to-right position, $p = 1, 2, \dots, s$, within an array of that size.

11. To a smaller extent the same possibility arises for the late-probe control condition, where the delay permits fixation shifts that could be used to reduce probe eccentricity (but not element eccentricity).

data from centered-array blocks for absolute-position effects.

9. Design details

9.1 Subjects

The four subjects in this experiment had extensive practice (more than 40 hours each) with spatial-location probes, having participated in a previous experiment in which performance with visual and tactile markers was compared (Sternberg, Knoll, & Turock 1986; Experiment 7). Subjects earned 7 dollars for each of four experimental sessions, which were conducted on successive days and lasted about 50 minutes. They were given feedback about their mean *RTs* and numbers of errors after each block of 16 trials.

9.2 Order of conditions

The eight conditions in the experiment were generated by crossing the four information/delay conditions described above (early-probe control, late-probe control, advance location information, and advance identity information) with two array-type conditions.

In addition to our standard *distributed-array* condition, in which an array of size s on a particular trial can occupy any one of the $7-s$ possible contiguous subsets of the six display locations, subjects also had experimental sessions in a *centered-array* condition, in which arrays were always centered in the display area.

The four information/delay conditions were blocked within the two array-type conditions, with the latter held fixed for a pair of successive days. On any one day the order of the principal conditions for individual subjects was determined by a *balanced latin square* in which each condition followed every other condition exactly once (Edwards, 1950). On the second day of each pair the order of the principal conditions was reversed for each subject, producing another balanced latin square. Two subjects had distributed arrays for the first pair of days followed by centered arrays for the second pair; the remaining two subjects had centered followed by distributed arrays. Each subject had the same order of information/delay conditions on the first pair of days as on the second such pair.

9.3 Distributed-array sessions

In the distributed-array condition we presented arrays containing 2, 3, 5, and 6 digits. Within a display area that contains six possible element locations an array of size s can occupy $7-s$ array positions. Moreover there are s serial positions within the digit array giving a total of $s(7-s)$ trial types (combinations of array position and serial position).

For $s = 3$ the combining of four array positions and three serial positions gives 12 trials. The following adjustments were made to produce 12 trials for each other

array size. (See Figure 5.) For $s = 2$, we added one trial with the probe in the leftmost display location and one trial with the probe in the rightmost display location to the 10 trial types that result from the combination of five array positions and two serial positions. (See Figure 5.) For $s = 5$, two array positions and five serial position result in 10 trial types. We again added one trial each with the probe in the leftmost and rightmost display locations. For $s = 6$, there is only one array location; we replicated each serial position to give a total of 12 trials.

9.4 Centered-array sessions

Since the arrays were always centered in these sessions, the only variation was the serial position of the probe. We presented arrays of size 2, 4, and 6 digits, and replicated each serial position 8, 4, and 3 times, respectively, to give a total of 16 trials for each array size.

9.5 Construction of trial sequences

The target digit was chosen randomly with the constraint that occurrence frequencies of digits in the set 0, 1, . . . , 9 were as uniform as possible within trials of the same array size and similar array and serial positions. (Thus in assigning target digits to trials we used sequences of permutations of the set of targets rather than sampling with replacement.) The order of trial types defined by size, array position, and serial position was random. The choice of digits other than the target digit was random subject to the following constraints applied to the whole array: all digits distinct, no subsequence $n, n+1, n+2$ (e.g., 567), no subsequence $n, n-1, n-2$ (e.g., 321), no subsequence $n, n+2, n+4$ (e.g., 468), and no subsequence $n, n-2, n-4$ (e.g., 531).¹²

The randomization was performed separately for each subject and for each of the four conditions within each of the four sessions.

9.6 Size of experiment

In each of our eight conditions and for each subject we ran a total of 96 trials, distributed over the two days in a pair. This is substantially less than the amounts of data collected previously in our experiments with spatial-location probes. For example, in Sternberg, Knoll, & Turock 1986, Experiment 7, we collected about 500 trials per subject per condition. Our goals in the present experiment were limited: We wished primarily to estimate overall magnitudes of the array-size effect, measured in terms of the slope of the $RT(s)$ function, which we assume, based on other studies, to be linear, rather than testing the form of the function or, for example, examining the

12. These constraints applied modulo 10. Thus if 321 was excluded, so were 210 and 109.

absolute position effects in detail.

10. Method of data analysis

10.1 *More on experimental design: The need for regression analysis*

In assessing the effect of array size (our principal goal) a number of secondary factors that are also known to influence performance must be considered, as mentioned in Section 4. The reasons they must be considered explicitly are twofold: In some cases we select their levels randomly because the experiment is too small to permit complete balancing, and in other cases an orthogonal design is impossible and there is some degree of inherent confounding. Indeed, it is for this reason that an explicit multiple regression method is necessary rather than a more standard analysis suitable for multiway tables.

The main secondary factors are as follows: First, there is the serial position of the target element within the array. Because the number of serial positions changes from one array size to another, and because we cannot specify a correspondence between positions in arrays that differ in size, we treat serial position as a separate effect for each array size. Second, there is the position of the target (and hence of the probe) within the display area: its "absolute position". Our previous findings have forced our model of the absolute position effect to be somewhat complicated: the effect seems to be systematically smaller for targets that are the leftmost or rightmost elements of an array — end elements — than for interior elements.¹³ The difference between end elements and interior elements generates an interaction between serial position and absolute position, which is embedded in the multiple regression model that we fit to the data. The third main secondary factor is the identity of the target element — the element that must be identified and named. Some target elements are associated with longer *RTs* than others, possibly because of identification-time differences, or differences in naming latency given the identity, or differences in measurement delay of our speech-onset detector (possibly related to the initial sound of the spoken name).

13. This effect in *RT* data is similar to the phenomenon that Wolford (1975, Figure 2) has reported for discrimination data: The decremental effect of retinal eccentricity on the accuracy of identifying a target letter is greater when that letter has neighbors on both sides than on only one side. Furthermore, if having neighbors on both sides rather than only one (as in the case of interior elements) can be regarded as a source of degradation, then the phenomenon is also similar to Eriksen & Schultz's (1977) finding that the effect of eccentricity on naming an isolated letter is increased when the letter is degraded (by a superimposed field of dots).

10.2 The Regression Model

The regression model can be expressed as follows, where \overline{RT} denotes mean RT :

$$\overline{RT} = \mu_t + \alpha_s + \beta_{si} + \gamma_p + \delta_d.$$

There are two means parameters $\{\mu_t\}$, one for distributed and one for centered arrays. The $\{\alpha_s\}$, which represent the array-size effect, are defined in two separate sets. For distributed arrays, we let $s = 2, 3, 5$, and 6 , and for centered arrays we let $s = 2', 4'$, and $6'$. Each set is constrained to sum to zero, and they thus reflect 3 and 2 degrees of freedom (df), respectively. Although the present experiment is too small to provide an adequate assessment of linearity, for which it was not designed, we wanted the analysis to be able to reveal any salient nonlinearity if such should exist under the new experimental conditions. For this reason we decided against the option of *constraining* the array size parameters $\{\alpha_s\}$ in each of the two sets to be linear and estimating just a slope parameter in each set. Instead, we allowed the $\{\alpha_s\}$ to vary independently of each other (except for the constraint that within each set they sum to zero). As our measure of the array-size effect we used the slope of a linear array-size function $RT(s)$ fitted by ordinary least squares to each of the sets of estimates of the $\{\alpha_s\}$.¹⁴ The $\{\beta_{si}\}$, which represent the serial-position effects, are defined for array sizes $s = 2, 3, 4, 5$, and 6 , and for positions $i = 1, 2, \dots, s$ within each array size; they are constrained to sum to zero for each s -value. These parameters thus reflect 15 df .¹⁵ The $\{\gamma_p\}$ represent the two assumed absolute-position effects, one for end elements, defined for $p = 1, 2, 3, 4, 5$, and 6 , and constrained to sum to zero, and the other for interior elements, defined for $p = 2^*, 3^*, 4^*$, and 5^* , and constrained separately to sum to zero. The absolute-position effects therefore reflect 8 df . The $\{\delta_d\}$ represent the element-identity effect and are defined for $d = 0, 1, \dots, 8$, and 9 , and constrained to sum to zero, thus reflecting 9 df . Finally, the two values of μ_t brings the number of degrees of freedom in the model being fitted to the data to 39.

14. The estimated slope, even of a nonlinear function, can be regarded as an estimate of the mean effect of an increment of one unit in the factor of interest — here, array size.

15. Note that as a consequence, the array sizes in common to centered and distributed array conditions ($s = 2, 6$) are fitted with a common set of serial-position parameters. Data for centered and distributed arrays are also fitted with a common set of absolute-position parameters. We find it plausible that these effects are independent of whether the data are collected in a session with centered arrays exclusively, or with distributed arrays. Fitting them jointly to data from both types of array has the virtue of providing more data on which their estimates can be based. Furthermore, we are forced to treat the data from centered arrays in the same regression as the distributed-array data because data from the centered arrays alone are insufficient to permit estimation of both serial-position and absolute-position effects. One way to test the invariance assumptions that we are therefore forced to make is to compare parameter estimates (or appropriate fitted values) from a regression based on distributed arrays alone with corresponding values from the joint regression. Such a comparison is reported in Appendix 2.

For each of the eight conditions in the experiment and for each subject, we ran 96 trials distributed over two successive days. After deleting the error trials from each of these sets of 96 we were left with about 93 trials in each of 32 sets. We fitted the regression model to each of these 32 sets. The 39 independent parameters derived from each set of data should be regarded as a description of the data set; we combined subsets of these parameters to provide summary descriptions of the data.

For centered arrays, in which the confounding of array size with retinal eccentricity is severe, we believe that the fitting of a regression model that permits "correcting for" the eccentricity effect is especially useful, and that a conventional *cell-means analysis*, although straightforward, is likely to give results that are especially biased.¹⁶ To test this belief and, more generally, to better understand our method of data analysis, we used two additional methods to analyze the data from the present experiment. One method is a cell-means analysis, while the other is the fitting of the regression model described above, but with absolute-position parameters, $\{\gamma_p\}$, omitted (i.e., assuming no effect of absolute position). A comparison of the three methods of analysis is provided in Appendix 1.

10.3 Method of fitting the regression model

In a recent study we compared ordinary least squares regression to Huber's robust iteratively reweighted least-squares method applied to data from a large experiment using spatial-location probes (Sternberg, Turock, & Knoll, 1986). We discovered that with respect to several criteria, the robust method is to be preferred: applied independently to different data sets within the same experiment, the robust method provides characterizations of the data that are more orderly, in the sense that factor effects (i.e., parameter values) are more uniform, and residual variability after such effects are removed is substantially smaller.

We used the variant of robust regression that embodies the Huber weighting function with constant 1.345. For readers unfamiliar with this method we provide a brief description. (See Coleman, Holland, Kaden, Klema, & Peters, 1980; Hampel, Ronchetti, Rousseeuw, & Stahel, 1986; Hoaglin, Mosteller, & Tukey, 1983)

Suppose we have a set of parameter estimates; the first such set might be obtained by ordinary least squares regression; later sets are obtained by iteration. Let r_i be the set of residuals obtained by fitting the model with a particular set of parameter estimates to one of our data sets (of approximately 93 observations). Define μ as a scale parameter given by the median absolute residual divided by 0.6745. Now define a weight, w_i , as follows:

16. See Appendix 1 for a more precise definition of a cell-means analysis.

if $|r_i| \leq 1.345u$, then $w_i = 1$;

$$\text{if } |r_i| > 1.345u, \text{ then } w_i = \left\{ \frac{1.345u}{|r_i|} \right\}^{1/2}.$$

Thus, all observations contribute to the solution, and observations that differ from the model prediction based on the last set of parameter estimates by no more than 1.345 estimated scale units are given unit weight, whereas observations that differ by more than that amount are increasingly downweighted. The iterated set of parameter estimates is now obtained by minimizing the sum of squared *weighted* residuals, where each residual r_i is weighted by w_i . The iteration continues until a criterion of convergence is met.

11. Results

11.1 Effects of array size under eight conditions

The points plotted in Figures 6 and 7 are the means over subjects of the estimated values of parameters $\{\mu, + \alpha_s\}$ for each of the four conditions in distributed (Figure 6) and centered (Figure 7) arrays, together with the linear $RT(s)$ functions fitted by (ordinary) least squares to each of the four sets of points. The parameter estimates result from the application of robust regression to our data, as described above. Although the experiment was not designed to assess the linearity of these array-size functions, they appear to be adequately linear.¹⁷ It follows that the slope is a good measure of the array-size effect, which is the focus of the experiment. Slopes of the fitted array-size functions for individual subjects are displayed in Table 1 for each of the four conditions and for each array type. Also shown for each individual are the mean slopes over the three early conditions (*Early*, *Ident*, and *Loc*) which we combine because, as we shall see, they do not differ reliably.¹⁸

17. To search for systematic nonlinearity we used ordinary least squares to fit quadratic functions to the estimated values of parameters $\{\mu, + \alpha_s\}$ for each subject in each of the eight conditions, and evaluated the resulting quadratic coefficients by means of analysis of variance. Factors (and numbers of levels) in the analysis are *subjects* (4), *array type* (2), *information/delay condition* (4), and *order of array types* (2; between subjects). We found that neither the grand mean ($-0.79 \pm 1.13 \text{ msec/element}^2$) nor any of the effects or interactions were significant. Suppose that the function in question ranges over display sizes of from two to six elements. Then a quadratic function whose quadratic coefficient has a value equal to the grand mean has the property that the value for array-size 4 lies 3.2 msec below a linear function that joins the values for array sizes 2 and 6.

18. Note the unusually small slope estimate for subject 2 with distributed arrays in the late-probe condition. This subject also has unusually large absolute-position parameters in the leftmost positions for both interior and end elements, and shows slopes that are less unusual in the other analyses discussed in Appendix 1.

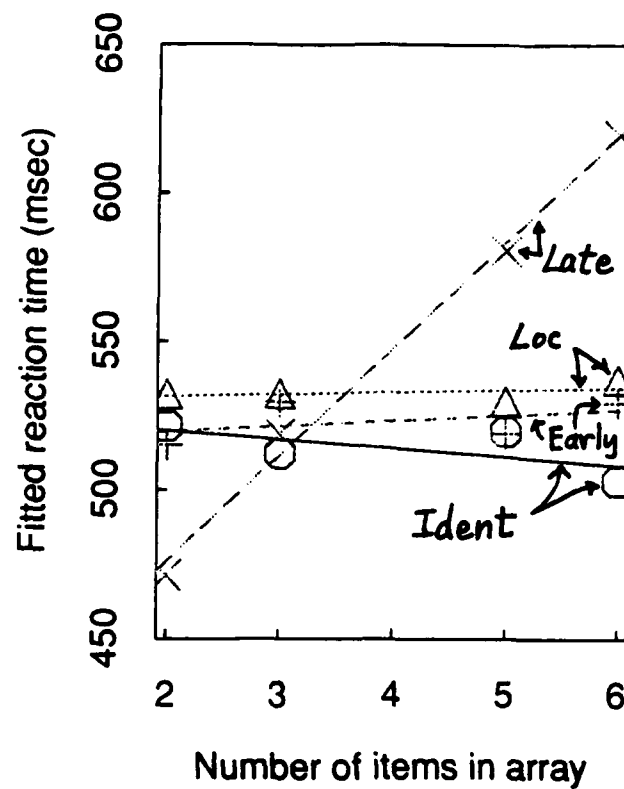


Figure 6. Mean over subjects of estimated "true reaction time" ($\hat{\mu}_i + \hat{\alpha}_i$) as a function of array size, s , for each of the four information/delay conditions in sessions with distributed arrays. Also shown for each condition is a linear function fitted by least squares. The conditions are *Early* (Early probe control, plus signs), *Late* (Late probe control, times signs), *Ident* (Advance identity information, circles), and *Loc* (Advance location information, triangles).

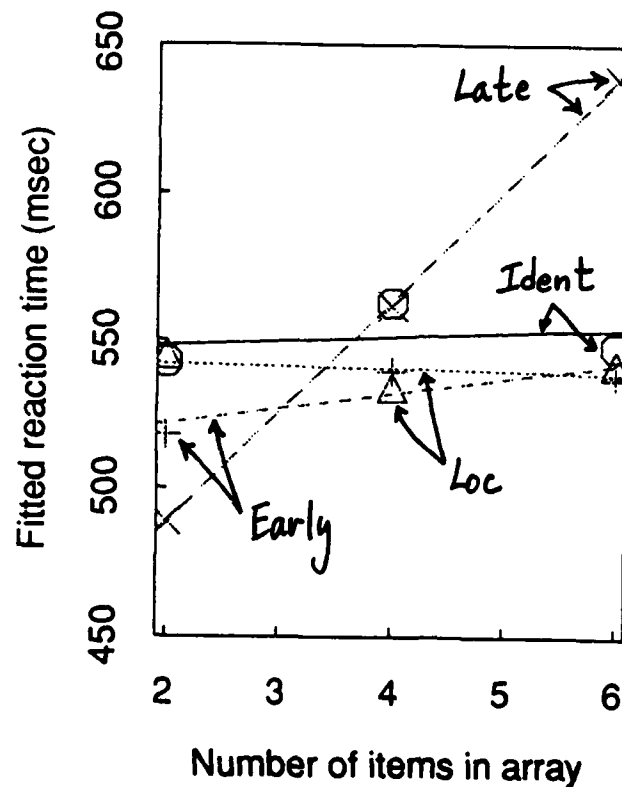


Figure 7. Mean over subjects of estimated "true reaction time" ($\hat{\mu}_t + \hat{\alpha}_t$) as a function of array size, s , for each of the four information/delay conditions in sessions with centered arrays. Also shown for each condition is a linear function fitted by least squares. The conditions are *Early* (Early probe control, plus signs), *Late* (Late probe control, times signs), *Ident* (Advance identity information, circles), and *Loc* (Advance location information, triangles).

Slopes										
Subject	Distributed Arrays					Centered Arrays				
	Early	Late	Ident	Loc	Early*	Early	Late	Ident	Loc	Early*
1	0.5	40.6	-2.0	8.2	2.2	8.2	33.8	3.1	1.2	4.1
2	3.7	8.3	-5.8	-8.3	-3.5	4.1	22.3	14.9	-5.7	4.4
3	-0.5	43.3	3.5	-1.9	0.3	-1.1	44.8	-0.9	-0.5	-0.8
4	3.7	51.2	-7.2	5.0	0.5	9.0	49.0	-11.6	1.9	-0.2
Mean	1.8	35.9	-2.9	0.7	-0.1	5.0	37.5	1.4	-0.8	1.9

Table 1. Array-size effects based on full regression analysis. Values are slopes of linear $RT(s)$ functions fitted to estimated array-size parameters. Column-head definitions: *Early* = Early probe control; *Late* = Late probe control; *Ident* = Advance identity information; *Loc* = Advance location information; *Early** = Mean of Early, Ident, and Loc conditions (all with -50 msec probes). Estimated SE for each of the first four means in each set, based on 6 *df* in the analysis of variance discussed in Section 11.2, is 2.3 msec. Estimated SE for the fifth mean in each set is 1.3 msec.

11.2 Statistical analysis

To test the slope effects of interest and to develop an estimate of residual error to use in evaluating the mean slopes, we ran an analysis of variance on the estimated slopes, with the factors (number of levels) *subject* (4), *array-type condition* (2), *information/delay condition* (4), and *order of array types* (2; between subjects). We treat as a residual the mean square associated with the 6-*df* interaction of information/delay condition, array-type condition, and subject within array-type order; its value is 21.329 *msec*². This provides an estimate of 2.3 *msec* as the SE of the mean slope for each of the eight conditions, and 1.3 *msec* as the SE for the mean slope over the three early conditions, for each array type. According to this analysis, the grand mean differs significantly from zero ($p < .05$), not surprisingly, given the large slope values for the late conditions. Furthermore, there is a significant ($p < .001$) effect of information/delay condition, again, not surprising, given the large differences in slope between the six early conditions and the two late conditions. At $p = .05$, no other effects or interactions are significant.

Given these results we wished to determine which of the differences between means in Table 1 are statistically significant. We employed Tukey's HSD method of applying the studentized range. (See Winer, 1971.) This test indicates that the eight means fall into two sets: the six values for *Early*, *Ident*, and *Loc* conditions in one set, and the two values for *Late* in the other. Within sets, and at the $p = .05$ level, the values do not differ significantly, whereas between sets they do ($p < .01$).

We also wish to know which of the slopes differ significantly from zero, particularly for the six slopes from early-probe conditions. We thus have the problem of comparing each of eight means to a fixed constant. This problem is similar to comparing a set of treatments to a control, except that here the quantity that corresponds to the mean of the control condition is a fixed constant (zero) instead of being based on observations subject to sampling variability. We adapted Dunnet's (1955; see Winer, 1971) method to this case, multiplying the value of t from Dunnet's table by $\sqrt{MS_{error} / n}$ instead of $\sqrt{2MS_{error} / n}$, to derive the critical difference. This test indicates that none of the six means from the early-probe conditions differs significantly from zero ($p = .05$), but that the two means from the late conditions do so differ ($p < .01$).¹⁹

19. In addition to the analysis of variance of the full set of slopes described above, we also ran an analysis of the same kind, but restricted to the six early conditions. We did this because we have found in earlier work that between-subject slope differences grow with probe delay, and we wished to check whether inclusion of values for the late-probe conditions was inappropriately inflating the residual mean square. An F-test of the *grand mean* (0.89 *msec*) in this analysis revealed that it was not significantly greater than zero; this is consistent with the conclusion above that none of the six mean slopes differs significantly from zero. At the $p = .05$ level, no effects or interactions were significant. The residual mean square, based on 4 *df*, is 20.975, similar to the value in the full analysis.

Although the focus of our interest is in the influence of conditions on the array-size effect, and therefore on the *slopes* of the fitted linear functions, any difference among the three early-probe conditions is of interest. We therefore subjected the estimated *means* parameters to an analysis of variance that had the same structure as the slopes analysis. We found no significant effects or interactions.²⁰

11.3 Influence of information versus delay on the array-size effect

The principal question that our experiment was designed to answer is whether the influence of probe delay on the array-size effect is partly or wholly a consequence of the information about probe location or target identity that the delay permits the subject to acquire. We sought to answer this question by providing such information explicitly in the *Loc* and *Ident* conditions. Insofar as such information accrual plays a role, we would expect the array-size effects (measured by slopes) to be greater in the experimental conditions than in the *Early* control condition. As a measure of the size of effect we are trying to explain, we can use the difference between slopes for *Late* and *Early* control conditions. The relevant quantities are displayed in Table 2. We have already seen that only the first of each set of three differences is significant. That is, there is no evidence that advance information of either kind influences the function that relates mean *RT* to array size; hence no portion of the influence of delay on the array-size effect can be attributed to the reduction of uncertainty about either identity or location of the element to be retrieved. It is worth noting that not only can the magnitudes of the effects of advance information not be discriminated from zero, but that they are also significantly smaller than the effect of delay, and that these findings obtain separately for both distributed and centered arrays.

20. Despite the substantial slope difference, the means differ little (23.1 ± 7.3 msec) between the six early-probe and the two late-probe conditions.

Slope Differences						
Subject	Distributed Arrays			Centered Arrays		
	Late-Early	Loc-Early	Ident-Early	Late-Early	Loc-Early	Ident-Early
1	40.1	7.7	-2.6	25.7	-7.0	-5.1
2	4.7	-12.0	-9.5	18.2	-9.8	10.9
3	43.9	-1.3	4.0	45.9	0.6	0.2
4	47.6	1.3	-10.9	40.0	-7.1	-20.6
Mean	34.0	-1.1	-4.7	32.4	-5.8	-3.7

Table 2. Influence of advance information of two kinds on the array-size effect, compared to the influence of delay. Entries are differences between indicated pairs of the slopes shown in Table 1. See Table 1 for column-head definitions. Estimated *SE* for each of the six means, based on 6 *df* in the analysis of variance discussed in Section 11.2, is 3.3 msec.

11.4 Comparison of array-size effects in distributed versus centered arrays

A secondary issue in the experiment is the influence of array type on the array-size effect. There are two reasons for expecting such an influence: First, array size is more severely confounded with retinal eccentricity for centered than distributed arrays. We might therefore expect a larger array-size effect for the former. Insofar as the regression adjustment for the absolute position effects is adequate, however, any such difference should be eliminated. Second, although we exhorted subjects to point their eyes at the fixation mark under all conditions, and although they reported doing so, they might have been tempted, at least on some trials in the conditions with advance location information and with late probes, to move their eyes from the fixation mark to the center of the array, should those locations differ; With distributed (but not centered) arrays, the locations often differ. It seems likely that such eye movements would influence the array-size effect (although it is not clear to us which direction such an influence might take).

Slope Differences: Centered - Distributed				
Subject	Early	Late	Ident	Loc
1	7.6	-6.8	5.1	-7.0
2	0.4	13.9	20.8	2.6
3	-0.5	1.5	-4.4	1.4
4	5.3	-2.3	-4.4	-3.1
Mean	3.2	1.6	4.3	-1.5

Table 3. Influence of array type on the estimated array-size effect for four information/delay conditions. Entries are the differences between the slopes shown in Table 1 for centered and distributed arrays in the indicated condition. Estimated SE for each of the four means, based on 6 *df* in the analysis of variance discussed in Section 11.2, is 3.3 msec.

Table 3 shows the relevant differences between slopes for the four information/delay conditions. Although there is a tendency for estimates to be higher when derived from centered arrays, this tendency is significant neither by a binomial test based on the signs of the 16 differences, nor by the analysis of variance or the tests based on it that are described in Section 11.2. It would appear that the adjustment for absolute-position effects made by the regression analysis is essentially complete. In Appendix 1 we show that by fitting the effects of absolute position, as we have done in the present analysis, we cause the slope estimates for sets of centered and distributed arrays to converge.

11.5 Effects of target element, serial position, and absolute position on mean RT

The most striking finding in the analyses described above is the virtual equivalence of the array-size effects in the conditions with early probes: early-probe control, advance location information, and advance identity information. To compare these conditions further, with each other and with the delayed-probe condition, we examined the effects of the identity of the target element, its serial position, and its absolute position, by performing analysis of variance on the appropriate set of parameter estimates produced by the regression analysis.²¹

21. In each of these cases, the parameters in one or more sets are constrained to sum to zero, so that the number of degrees of freedom associated with a set is one less than the size of the set. We express the constraint within the regression model by equating one of the parameters in each set to a linear function of the others, and estimating just those others (the *reduced parameter set*). In general, we then use the linear function to provide an estimate of the missing parameter, thus producing a *full parameter set*. We have applied analysis of variance to the full parameter sets; the conventional number of degrees of freedom associated with each set of parameters must therefore be reduced by one.

Identity of the target element Here the analysis of variance had the same structure as the analysis described in Section 11.2, except that it also included the factor *target identity*. We found a highly significant digit effect ($p < .001$), with no significant interactions; mean digit parameters had a range of 63.1 msec. Thus there is no evidence from this source of any difference among the four information/delay conditions.

Serial position Here the analysis of variance had the same structure as the analysis described in Section 11.2, except that it also included the factor *serial position*. For array-size s the regression analysis led to estimates of $s-1$ independent parameters reflecting serial-position effects, for a total of 15 such parameters. We found a highly significant main effect of serial position ($p < .001$). In this case, however, we also found a significant interaction between the effect of interest (serial position) and condition ($p < .01$). This interaction reflects only the difference between early and late probes, however: When we repeated the analysis with just the six early-probe conditions, we found no significant interaction with serial position. For early-probe conditions the serial-position function tends to take the form of an inverted U ; for late-probe conditions the function tends to increase monotonically from left to right. For the largest array, $s = 6$, for example, the range of mean parameter values is 58 msec in the early-probe conditions, and 243 msec in late-probe conditions.

Absolute position Values of the fitted absolute-position parameters correspond to V -shaped functions for both end elements and interior elements for all conditions, with the functions for interior elements the steeper.²² The residual mean squares differed markedly ($p < .001$) for the two sets of parameters, reflecting substantially greater individual differences in the absolute position functions for interior elements. We therefore applied analysis of variance to the two parameter sets separately, using the same analysis structure as in the one described in Section 11.2, but also including absolute position as a factor. For interior elements there was a significant effect ($p < .005$) of position, with no significant interactions. For end elements, however, absolute position interacts significantly with conditions ($p < .005$). As in the case of serial position, this interaction reflects only the difference between early and late probes; when we repeated the analysis with just the six early-probe conditions, we found no significant interactions with absolute position. The effect of probe delay is

22. As slope measures in this case we use the means of the differences between absolute-position parameters that correspond to adjacent positions that the functions for interior and end elements share on the two sides of the V (positions 2 and 3 on the left, and 4 and 5 on the right). Over all conditions, the values of these mean position effects are 96.1 msec/position for interior elements, and 39.3 msec/position for end elements. The difference is 56.8 ± 21.2 msec/position, which is statistically significant ($p < .02$).

to increase the magnitude of the absolute-position effect for end elements.²³

11.6 Analysis of error rates

Method of analysis Although error rates are very low in the present experiment, averaging less than 3%, and are of secondary interest, we felt it was important to analyze them; it is possible that the benefits of advance information might be revealed by the accuracy as well as or instead of the speed of retrieval processes. Because of the inherent confounding in the experiment that is discussed in Section 10.1, regression analysis is appropriate for an adequate description of error rates, just as it is for RTs. For this reason, we applied the same regression model to both kinds of data. In this case, however, because an observation is either a zero (for no error) or a one (for error) we used ordinary least-squares regression rather than a robust method. Our principal aim in using the regression model was statistically to eliminate the confounding of array size and absolute position, to which centered-array conditions are especially subject.²⁴

Because our regression analysis placed no constraints on the fitted error rates, and because rates for some subjects and some conditions are very low, some fitted values returned by the regression analysis were negative. Our confidence in the appropriateness of the regression model was enhanced by the observation that very few such negative values were obtained, and that their magnitudes were close to zero.²⁵

Effects of information/delay condition, array size, and array type Mean fitted error rates — that is, the estimated parameters $\{\mu_i + \alpha_i\}$ — are shown as a function of information/delay condition, array type, and array size in Table 4, and as a function of information/delay condition and subject in Table 5.

-
23. One possible explanation of this increase with delay depends on the idea that the absolute position effect reflects differences in the time required to discriminate probe location relative to the array. When the probe is delayed, such differences are presumably fully reflected in the RT; When the probe occurs in close temporal proximity to the array, however, discrimination of its location may occur in parallel with processing of array elements, so that variation in location-discrimination time with retinal eccentricity would be partially or fully "masked" by the time required to discriminate the elements of the array. However, the interior elements do not show the increasing eccentricity effect with delay shown by the end elements, thus not supporting this conjecture.
24. We also performed a more conventional (cell-means) analysis and compared the two sets of results. The differences are noticeable, but do not appear to change qualitative features of the data.
25. Consider the 28 fitted values associated with the four information/delay conditions, the two array types, and the three and four array sizes within array type. Only six of these fitted values are negative, with a maximum magnitude of 0.35% and a mean magnitude of 0.19%; in contrast, of the positive fitted values, the maximum is 16.82% and the mean is 2.64%.

Error Rate (Percent)								
Array Size	Early		Late		Ident		Loc	
	Dist	Cen	Dist	Cen	Dist	Cen	Dist	Cen
2	1.1	0.7	2.1	1.6	2.1	1.6	0.0	-0.2
3	0.0		1.5		2.3		0.0	
4		0.2		10.4		1.9		0.0
5	-0.2		10.1		1.5		0.0	
6	-0.3	-0.4	15.4	16.8	0.8	2.1	0.2	0.7

Table 4. Effect of condition and array size on error rate for distributed (Dist) and centered (Cen) arrays. Entries are fitted error rates in percent, based on regression parameters.

See Table 1 for column head definitions.

Error Rate (Percent)				
Subject	Early	Late	Ident	Loc
1	0.0	10.4	1.3	0.0
2	0.0	8.9	0.0	0.0
3	0.6	5.0	3.3	0.4
4	0.0	8.8	2.4	0.0
Mean	0.2	8.3	1.8	0.1

Table 5. Effect of information/delay condition on error rates for individual subjects. Entries are fitted error rates in percent, based on regression parameters. See Table 1 for column head definitions.

To determine the reliability of effects we subjected these values to analyses of variance with the factors (number of levels) *subject* (4), *information/delay condition* (4), *array type and size* (combined; 7), and *order of array types* (2; between subjects). We applied the first such analysis to all four information/delay conditions, and found highly significant ($p < .01$) effects of condition, array type/size, and their interaction. Tukey's method (see Section 11.2), applied to the four condition means, indicated that the *late-probe* condition differed from the early-probe conditions ($p < .01$), which (at the $p = .05$ level) did not differ significantly from each other. In the second analysis, which was limited to the three early-probe conditions, neither the array type/size effect nor its interaction with information/delay condition proved to be reliable; however, the condition effect ($p < .01$) and its interaction with array-type order ($p < .05$) were significant. The difference in results appears to be due to inhomogeneity of variance, with the late-probe condition contributing disproportionately. When the residual from the second analysis is used with Tukey's method to examine the differences among the three early-probe conditions, we find that the *ident* condition is significantly different from the other two conditions ($p < .01$), which (at the $p = .05$ level) do not differ significantly. This is the first instance we have seen of a reliable difference among the

early-probe conditions. It is worth noting, however, that although the error rate in *ident* is higher than in the other early-probe conditions, and thus less dissimilar to the late-probe condition than the others, it is still highly dissimilar, and that unlike the late-probe condition, error rate does not increase with array size in *Ident*.

These statistical tests, considered in combination with the information in Tables 4 and 5, suggest the following description of error rates. First, in no case is there an effect of array type. Second, there is a substantial effect of array size in the late-probe condition, but not elsewhere. Thus, the fitted error rate rises from about 2% (array size 2) to 16% (array-size 6) in that condition, but remains relatively constant over array size in the early-probe conditions. Third, it is in the late-probe condition that the mean error rate is highest, averaging 8.3%. And fourth, error rate is very low in the early-probe control and advance location information conditions (0.2% and 0.1%, respectively), but is higher (1.8%) in the advance identity information condition.

12. Conclusions

This study was designed to assess the roles of uncertainty about position, target, and response, and changes in such uncertainty with probe delay, in producing the dramatic effects of storage time we have observed on the retrieval of visual information specified by location. To make this assessment we constructed two new experimental procedures.

In the procedure that provided *advance location information* we manipulated the subject's knowledge of the set of alternative locations that might be queried by the probe. Insofar as *spatial uncertainty* plays a role in processing of the probe, we expected that this manipulation would especially benefit small arrays, and thus would increase the slope of the function that relates mean *RT* to array size, the *RT(s)* function.

In the procedure that provided *advance identity information* we manipulated the subject's knowledge of the set of alternative target stimuli and responses. Insofar as *stimulus uncertainty* and *response uncertainty* play roles in generation of the response, we expected that this manipulation would also be especially beneficial for small arrays, and thus would also increase the slope of the *RT(s)* function.

In sharp contrast to these expectations, we found no effect of our manipulations on the slope of the *RT(s)* function. This reduces the likelihood that the dramatic increase in slope with probe delay is associated either with operations that precede access to the internal representation of the array (processing of the probe), or with operations that follow such access (generation of the response). By excluding these alternative accounts of the increase in slope with probe delay, we have strengthened the argument that favors an explanation in terms of loss of a *direct-access* property as an initial *random-access memory* is transformed into a *sequential-access memory*.

A secondary issue that we explored in the present study is the relation between performance with distributed arrays, which may encourage eye-movements under some

conditions, and centered arrays, which should not, but which suffer from serious confounding of array size and retinal eccentricity of array elements. We attempted to deal with this problem of confounding (as well as with the inherent nonorthogonality of an array-size experiment even with distributed arrays) by employing a regression analysis that was designed to estimate and "correct for" the effect of eccentricity (as well as other effects). Our results indicate that the "correction" was adequate, in the sense that performance measures were relatively invariant across distributed and centered arrays.

In two Appendices we consider our method of analysis relative to alternative methods, and provide evidence that favors our method, and also favors the use of distributed rather than centered arrays.

References

- Averbach, E., & Coriell, A. S. (1961)
Short-term memory in vision.
Bell System Technical Journal, 40, 309-328.
- Coleman, D., Holland, P., Kaden, N., Klema, V., & Peters, S. C. (1980)
A system of subroutines for iteratively re-weighted least-squares computations
Association for Computing Machinery Transactions on Mathematical Software, 6, 327-336.
- Davis, E. T., Kramer, P., & Graham, N. (1983)
Uncertainty about spatial frequency, spatial position, or contrast of visual patterns
Perception & psychophysics, 33, 20-28.
- Dunnet, C. W. (1955)
A multiple comparison procedure for comparing several treatments with a control
Journal of the American Statistical Association, 50, 1096-1121.
- Edwards, A. L. (1950)
Experimental Design in Psychological Research
New York: Rinehart & Company, Inc.
- Eriksen, C. W., & Hoffman, J. E. (1973)
The extent of processing of noise elements during selective encoding from visual displays.
Perception & Psychophysics, 14, 155-160.
- Eriksen, C. W. & Hoffman, J. E. (1974)
Selective attention: Noise suppression or signal enhancement
Bulletin of the Psychonomic Society, 4, 587-589.
- Eriksen, C.W. & Schultz, D. W. (1977)
Retinal locus and acuity in visual information processing
Bulletin of the psychonomic society, 9, 81-84.
- Hake, H. W. & Garner, W. R. (1951)
The effect of presenting various numbers of discrete steps on scale reading accuracy.
Journal of experimental psychology, 42, 358-366.
- Hampel, E. M., Ronchetti, E. M., Rousseeuw, P. J. & Stahel, W. A. (1986)
Robust Statistics: The approach based on influence functions
New York: Wiley
- Hoaglin, D. C., Mosteller, F. & Tukey, J. W. (Eds.) (1983)
Understanding robust and exploratory data analysis.

New York: Wiley

Holmgren, J. E. (1974)

The effect of a visual indicator on rate of visual search: Evidence for processing control.

Perception & Psychophysics, 15, 544-550.

Kroll, N. E. A. & Shepeler, E. M. (1985)

Visual priming effects as a measure of short-term visual memory.

American Journal of Psychology, 98, 449-468.

LaBerge, D. (1983)

Spatial extent of attention to letters and words

Journal of experimental psychology: Human perception and performance, 9, 371-379.

Proctor, R. W. (1981)

A unified theory for matching-task phenomena.

Psychological Review, 88, 291-326.

Shaw, M. L. (1978)

A capacity allocation model of reaction time

Journal of experimental psychology: Human perception and performance, 4, 586-598.

Shaw, M. L. (1984)

Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments

In H. Bouma & D. G. Bouwhues (Eds.), *Attention & Performance X*
Hillsdale, N J: Erlbaum

Sternberg, S. (1969)

The discovery of processing stages: Extensions of Donders' method.

In W. G. Koster (Ed.) *Attention and Performance II*, *Acta Psychologica*, 30, 276-315.

Sternberg, S., Knoll, R. L., & Turock, D. L. (1985)

Direct access by spatial position in visual memory: 1. Synopsis of principal findings.

Unpublished Manuscript

Sternberg, S., Knoll, R. L., & Turock, D. L. (1986)

Direct access by spatial position in visual memory: 1. Visual location probes.

Unpublished Manuscript

Sternberg, S., Turock, D. L., & Knoll, R. L. (1986)

Steps toward an empirical evaluation of robust regression applied to reaction-time

data.

Unpublished Manuscript

Teichner, W. H. & Krebs, M. J. (1974)

Laws of visual choice reaction time
Psychological Review 81, 75-98.

Theios, J. (1975)

The components of response latency in simple human information processing tasks
In P. M. A. Rabbitt & S. Dornic (eds.), *Attention and performance V*,
London: Academic Press, Pp. 418-440.

van der Heijden, A. H., Schreuder, R., & Wolters, G. (1985)

Enhancing single-item recognition accuracy by cueing spatial locations in vision
Quarterly journal of experimental psychology, 37A, 427-434.

Walker, P. (1978)

Short-term visual memory: The importance of the spatial and temporal separation
of successive stimuli.
Quarterly Journal of Experimental Psychology, 30, 665-679.

Welford, A. T. (1980)

Choice reaction time: Basic concepts.
In A. T. Welford (ed.), *Reaction times*
London: Academic Press, Pp. 73-128.

Winer (1971)

Statistical principles in experimental design, 2nd Edition.
New York: McGraw Hill

Wolford (1975)

Perturbation model for letter identification.
Psychological Review, 82, 184-199.

Appendix 1: Comparison of three analysis methods

In this study we described the behavior of interest by means of the estimated parameters in a regression model that was separately fitted to the data for each subject in each of the eight conditions. It was aspects of this description that we then presented and subjected to statistical analysis. Our principal reason for using the results of a regression analysis as an intermediate step, rather than using more conventional summary statistics, is the inherent nonorthogonality of our experimental design, especially because of the confounding of absolute position with array size. A secondary reason is our belief that *RT* distributions are inevitably contaminated, such that in some situations, of which we regard this study as an example, robust methods of analysis may produce results that are closer to the "truth". (See Sternberg, Turock, & Knoll, 1986, for a discussion.) In a very large experiment the desired insensitivity to contamination can perhaps be achieved by applying a robust measure of location separately to the data in each "cell". In a small experiment such as the present one, however, one needs the added power that is obtained by assuming constraints on the relations among the estimated location measures associated with different cells — constraints that are expressed by a regression model. The model we used is one that we had selected for substantially larger experiments using similar procedures (Sternberg, Knoll, & Turock, 1985, 1986). The desired insensitivity to contamination could then be achieved by using a robust method to fit the regression model.

Because our method is relatively unfamiliar, it seems desirable to compare the results that it produces with the results of other methods. In the present Appendix we consider two others.

A1.1 Cell-means analysis

By a *cell means analysis* we refer to a more conventional approach in which the data set for a subject and condition is regarded as falling into a set of subsets (*cells*), and in which the initial characterization is in terms of the means of each of these subsets. Cells in this experiment were defined for each serial position and array position within each array size (and for each subject and for each of the eight conditions). The value for each array size was taken to be an equally-weighted mean of the set of serial-position means; for distributed arrays, each serial-position mean was itself obtained by averaging (with equal weights) over array positions. The array-size effect was then taken to be the slope of a linear array-size function fitted by ordinary least squares to the set of array-size means. Note that absolute position does not enter directly into the cell means analysis, because absolute position is orthogonal with neither serial position nor array size, the confounding being especially severe for centered arrays.

Slopes Based on Cell-Means Analysis										
Subject	Distributed Arrays					Centered Arrays				
	Early	Late	Ident	Loc	Early*	Early	Late	Ident	Loc	Early*
1	-2.5	40.3	3.0	12.3	4.3	12.0	56.5	10.2	12.5	11.5
2	3.9	20.7	-7.8	-5.0	-3.0	11.4	58.1	15.7	6.2	11.1
3	1.1	41.7	0.2	-0.3	0.4	13.1	57.6	8.6	12.2	11.3
4	3.7	63.0	-3.8	5.5	1.8	18.9	64.8	-1.3	19.3	12.3
Mean	1.5	41.4	-2.1	3.1	0.9	13.9	59.2	8.3	12.5	11.6

Table A1. Array-size effects based on cell-means analysis. Values are slopes of linear functions fitted to array-size means. See Table 1 for column-head definitions.

The resulting slope estimates are displayed in Table A1, in which the values are arranged in the same way as in Table 1, to facilitate comparison. Two features are particularly worthy of comment. First, the principal substantive result of the study is shown as clearly here as in Table 1: For both distributed and centered arrays, there is a substantial increase in the array-size effect as the probe is delayed, and neither advance identity information nor advance location information has a similar influence on the array-size effect. Second, according to the cell-means analysis the array-size effect is systematically greater for centered than for distributed arrays, a difference that appears for each information/delay condition for each subject, and whose average value is about 18 msec for delayed probes, and about 11 msec for early probes.

A1.2 Limited-regression analysis

The two most important differences between the robust regression analysis described in the text of the present report, and the cell-means analysis described above are, first, the inclusion of absolute-position effects in the regression model and, second, the differential down-weighting of large residuals that makes the analysis robust. To ascertain the relative contribution of these features to the difference between the results of the two methods we used the same robust regression procedure but fitted a regression model that contained no absolute-position effects. In other respects the analysis was the same as the full regression. The resulting array-size effects are shown in Table A2.

Slopes Based on Limited-Regression Analysis										
Subject	Distributed Arrays					Centered Arrays				
	Early	Late	Ident	Loc	Early*	Early	Late	Ident	Loc	Early*
1	3.3	50.7	4.1	11.6	6.3	13.9	59.1	17.0	11.9	14.3
2	4.7	25.0	-6.1	-7.5	-3.0	9.7	57.9	16.5	3.2	9.8
3	2.5	46.5	3.7	1.4	2.5	10.7	53.9	3.9	13.3	9.3
4	7.1	56.5	-3.8	11.3	4.8	18.4	61.4	0.8	17.3	12.2
Mean	4.4	44.7	-0.5	4.2	2.7	13.2	58.1	9.6	11.5	11.4

Table A2. Array-size effects based on limited-regression analysis. Values are slopes of linear functions fitted to estimated array-size parameters. See Table 1 for column-head definitions.

The two features of results of the cell-means analysis characterize these results also. Moreover, the magnitudes of the differences between measures of the array-size effect in the two analyses are small, with the mean absolute difference being 3.40 msec for distributed arrays, and 2.34 msec for centered arrays. The similarity is easier to evaluate by referring to Table A3, in which the differences between values in Tables A1 and A2 are displayed. To further evaluate the relation between results from limited-regression and cell-means analyses, we ran an analysis of variance on the values in the two tables, with the factors (number of levels) *subject* (4), *method* (2), *array-type condition* (2), *information/delay condition* (4), and *order of array types* (2; between subjects). Of the main effect and seven interactions involving *method*, only one (*method* \times *information/delay condition* \times *order of array types*) is significant ($p = .05$); we take this to be a Type-1 error.

Slope Difference: Limited-Regression - Cell-Means										
Subject	Distributed Arrays					Centered Arrays				
	Early	Late	Ident	Loc	Early*	Early	Late	Ident	Loc	Early*
1	5.8	10.4	1.1	-0.7	2.0	1.9	2.6	6.8	-0.6	2.8
2	0.8	4.3	1.7	-2.5	0.0	-1.7	-0.2	0.8	-3.0	-1.3
3	1.4	4.8	3.5	1.7	2.1	-2.4	-3.7	-4.7	1.1	-2.0
4	3.4	-6.5	0.0	5.8	3.0	-0.5	-3.4	2.1	-2.0	-0.1
Mean	2.9	3.3	1.6	1.1	1.8	-0.7	-1.1	1.3	-1.0	-0.2

Table A3. Differences between array-size effects provided by limited-regression and cell-means analyses. Values are differences between the slopes of linear functions shown in Tables A1 (cell means) and A2 (limited regression). If a value is positive, then the slope provided by the limited-regression analysis is the greater.

See Table 1 for column-head definitions.

It appears that as applied to the present data, robust regression *per se* does not systematically alter the pattern of results. Instead, it is the incorporation of absolute-position effects in the regression model that affects the results systematically. This

can be seen most easily by referring to Table A4, in which the differences between values in Table A2 (limited regression) and Table 1 (full regression) are displayed.

Slope Difference: Limited-Regression - Full-Regression										
Subject	Distributed Arrays					Centered Arrays				
	Early	Late	Ident	Loc	Early*	Early	Late	Ident	Loc	Early*
1	2.8	10.1	6.1	3.4	4.1	5.7	25.3	13.9	10.7	10.2
2	1.0	16.7	-0.3	0.8	0.5	5.6	35.6	1.6	8.9	5.4
3	3.0	3.2	0.2	3.3	2.2	11.8	9.1	4.8	13.8	10.1
4	3.4	5.3	3.4	6.3	4.3	9.4	12.4	12.4	15.4	12.4
Mean	2.6	8.8	2.4	3.5	2.8	8.2	20.6	8.2	12.3	9.5

Table A4. Differences between array-size effects provided by limited-regression and full-regression analyses. Values are differences between the slopes of linear functions shown in Tables A2 (limited regression) and Table 1 (full regression). A positive value means that the slope provided by the full regression analysis is smaller. See Table 1 for column-head definitions.

All except one of the values in the table are positive, and values are substantially greater for centered than distributed arrays. To evaluate the relation between results from full-regression and limited-regression analyses, we ran an analysis of variance on the values in Tables 1 and A2, with the factors (number of levels) *subject* (4), *method* (2), *array-type condition* (2), *information/delay condition* (4), and *order of array types* (2; between subjects). Of the main effect and seven interactions involving *method*, only two fail to be significant ($p < .05$), with the main effect ($p < .01$) and the interaction of *array-type condition* and *method* ($p < .001$) especially strong. Thus, the fitting of (and thus "correcting for") absolute-position effects diminishes the estimated array-size effect for both kinds of array, but especially for centered arrays. We believe that this occurs because it reduces or eliminates the effect of the confounding of array size with retinal eccentricity — a confounding whose degree is greater for centered than distributed arrays.

A1.3 Comparison summary

Array-size effects for late and early probes of distributed and centered arrays, and their differences, are shown in Table A5 for the three analysis methods: cell means, limited robust regression, and full robust regression. As already noted, there is little difference between values for the cell-means and limited-regression analyses. The most important point is expressed by the columns of differences between slopes based on centered versus distributed arrays. This difference declines as we move from the cell-means to the full-regression analyses, from about 14 msec to a negligible 2 msec (averaging over late and early probes). Furthermore, the change in the effect is much greater for centered arrays (15.7 msec) than for distributed arrays (3.3 msec).

Among the three analysis methods, the full regression analysis thus produces the greatest invariance of estimated array-size effects across distributed and centered arrays, and it is the centered arrays (whose size is strongly confounded with retinal eccentricity) for which the estimates depend most on the method of analysis; array-size effects estimated from data for distributed arrays are affected relatively little. We believe that these findings tend to support, first, the use of the full regression analysis, which best approximates a desired invariance across array types and, second, the use of distributed arrays, which best approximates a desired invariance across analysis methods.²⁶

Slopes						
Analysis	Distributed Arrays		Centered Arrays		Difference	
	Late	Early*	Late	Early*	Late	Early*
Cell-Means	41.4	0.9	59.2	11.6	17.8	10.7
Limited Reg	44.7	2.7	58.1	11.4	13.4	8.7
Full Reg	35.9	-0.1	37.5	1.9	1.6	2.0

Table A5. Mean array size effects based on three methods of analysis for distributed arrays, centered arrays, and their difference. Values are slopes of linear functions fitted to estimated array-size parameters. *Early** = Mean of *Early*, *Ident*, and *Loc* conditions.

Appendix 2: Implications of applying regression analysis jointly to distributed-array and centered-array conditions

As mentioned in Section 10.2, in our regression analysis we fit the same set of absolute-position parameters to data from sessions with distributed arrays and centered arrays, and for the array sizes in common to these two data sets ($s = 2, 6$), we also fit the same sets of serial-position parameters. Of fundamental importance to our characterization of the data, therefore, are the invariance assumptions embodied in these simplifications. The simplifications are forced on us by the strong confounding of array size with eccentricity in the centered-array condition, which prevents us from applying the full regression model to centered arrays alone. We can, however, apply the full analysis to data from distributed-array sessions only. This provides one way to test the invariance assumptions: For each information/delay condition we can compare parameter estimates from the joint analyses we have described in the main

26. The values in Table A5 for early probes show how easily an error could be made in testing for the property of direct access: If one used centered arrays, or even distributed arrays without adjusting for effects of eccentricity, one might be tempted to believe that even for early probes there is an array-size effect.

text of the present report with estimates from analyses of data from distributed-array sessions only. If performance with centered and distributed arrays can be characterized by (approximately) the same parameters, then estimates based on the joint and distributed-only analyses should be (approximately) the same. That is, parameter estimates should not change as a consequence of doubling the size of the data sets from distributed-array sessions by adding to each of them the corresponding data set from centered-array sessions.

To test this expectation we applied analysis of variance to the parameter estimates (or the estimated slope of the array-size function based on them) from regression applied to the joint data sets and to the distributed-only data set. Factors were *subjects, order of array types, information/delay conditions, data set, and parameter* (when more than one parameter was examined).

The parameters that are most critical to the present study are those associated with array size, from which we estimate slopes of the $RT(s)$ functions. Within the joint analysis, separate parameters are associated with the two array types. The most critical question, then, is how is the slope for distributed arrays influenced by the constraints imposed by fitting serial-position and absolute-position parameters that are common to distributed and centered arrays in the joint analysis. Mean slopes are shown in Table A6.

Mean slopes for distributed arrays				
Data Set	Early	Late	Ident	Loc
Dist only	2.7	34.8	-3.7	0.5
Cent & Dist	1.8	35.9	-2.9	0.7

Table A6. Slopes of $RT(s)$ determined from array-size parameters for distributed arrays derived from regression applied to distributed arrays only, and regression applied to centered and distributed arrays jointly. See Table 1 for column-head definitions.

Differences are negligible; in the analysis of variance, neither the main effect of data set nor any interaction involving data set is significant.

For serial-position parameters we applied a similar test, adding as a factor in the analysis described above one that embodies serial position within array size. For arrays of size 2, 3, 5, and 6, (common to distributed-only and joint analyses), there are 16 parameters. We found no significant interactions between data set and serial position.²⁷

27. Because parameter values sum to zero, main effects are identically zero.

For absolute-position parameters we applied a similar test with less pleasant results. Here the interaction of data set with absolute position is highly significant ($p = .002$) and some of the higher-order interactions are significant as well. One possible explanation is that centered versus distributed array conditions may induce different kinds of performance. A second possibility is that the model approximates the data poorly, so that increasing the number of trials of centered arrays substantially alters the set of compromises made by the regression method. Fortunately this phenomenon does not appear to have distorted our estimates of the array size effect, summarized in Table A6.